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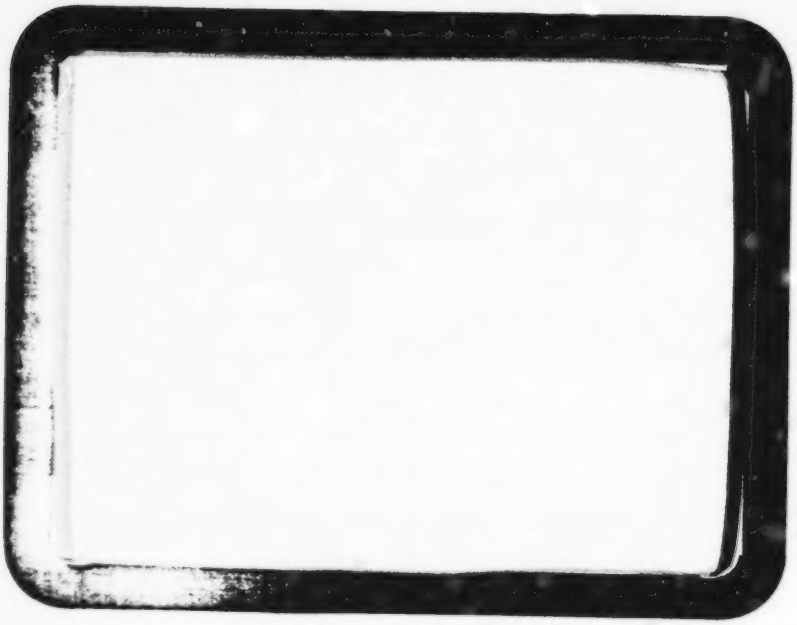

GOVERNMENT OF BRITISH COLUMBIA
FOREST SERVICE

A REVIEW OF LITERATURE TO 1975 OF FOREST HYDROLOGY PERTINENT TO THE MANAGEMENT OF MOUNTAINOUS WATERSHEDS

LAND MANAGEMENT REPORT NO. 2

BY

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INTRODUCTION

Forest management involves the modification of the forest canopy through harvesting. Timber harvesting is generally preceded by road construction and is usually followed by site preparation for regeneration purposes. These modifications to the canopy and soil alter the hydrologic nature of the harvested site, and depending on the size of the area harvested can lead to changes in the hydrologic characteristics of the watershed.

The following discussion is a review of selected forest hydrology literature dealing with the influence of forest management on the site hydrology of mountainous areas.

FOREST MANAGEMENT PRACTICES AND SITE HYDROLOGY

Site hydrology is the study of water in all its forms on, in and over the site, including its distribution, circulation and behaviour, its chemical and physical properties, and the reaction of the environment on water. While there still remains much to learn on the subject, it is clearly evident that site hydrology is modified by forest management practices. Whether the resulting modifications are desirable or not, they are at least in part an inevitable consequence of forest management. For this reason a knowledge of hydrologic processes will enable the forest manager to foresee the hydrologic modifications involved with various management options.

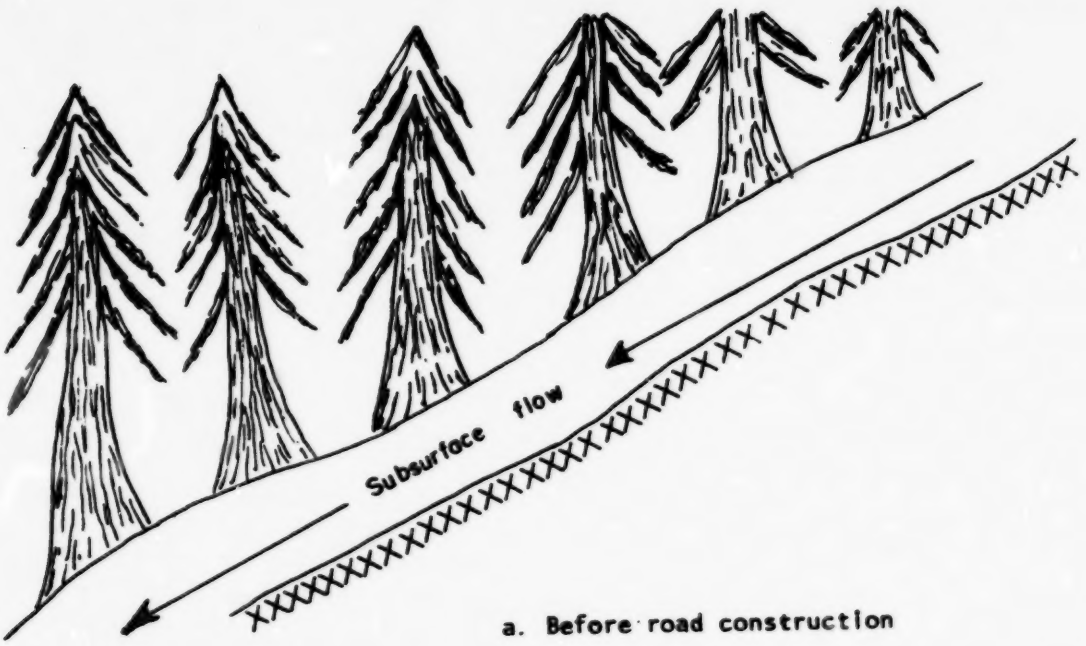
In order to discuss the hydrologic modifications to a site, forest management practices are divided into three components: forest roads, forest harvesting, and silvicultural site treatments.

A. Forest Roads

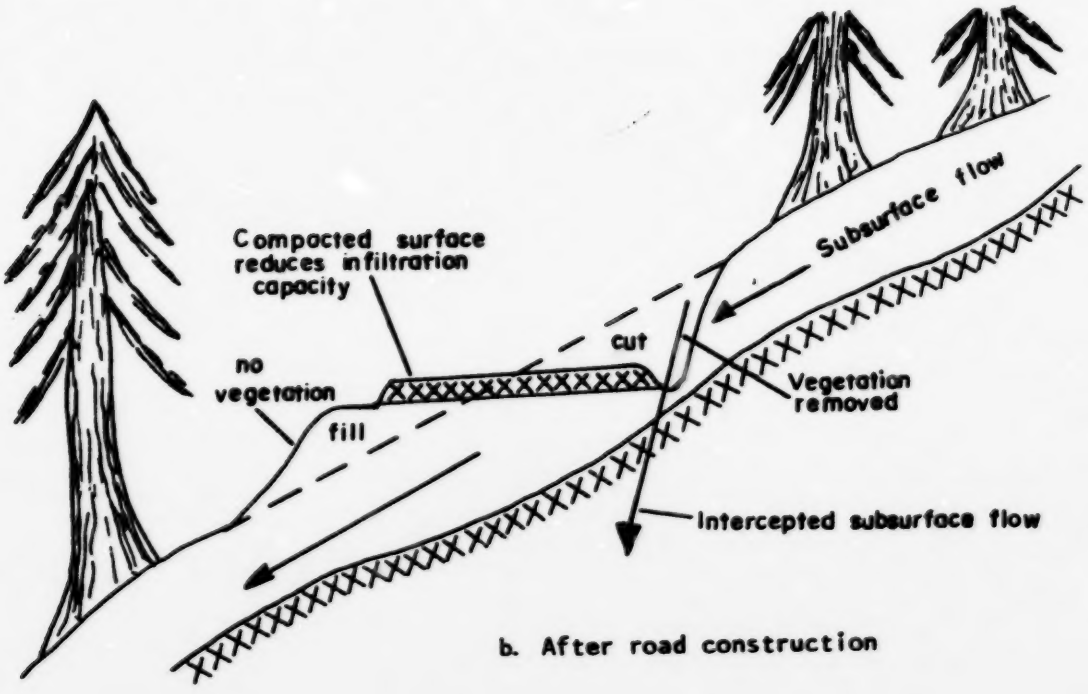
Forest roads have a number of hydrologic influences upon a mountainous site (Figure 1).

1. Interception of subsurface flows

When water, either in the form of rain or following the onset of snowmelt, comes in contact with the soil, the infiltration capacity determines whether the water will infiltrate and become soil water or whether it will flow overland as surface runoff. In this section we are concerned with water which becomes soil water. A portion of this water moves downslope under the influence of gravity and is termed



a. Before road construction



b. After road construction

Figure 1. Forest road and slope hydrology.

subsurface flow.

Subsurface flow maintains the water and nutrient supply to downslope vegetation. It thus plays a significant role in determining site productivity, particularly during periods of high soil water demand which can occur in late summer.

Forest roads affect subsurface flow by intercepting the water at the cut slope and channelling it down ditches or roadways as surface runoff. However, before the soil water emerges, the soil must be at or near saturation. This condition leads to potential instability of the cut bank through three mechanisms:

a. The filling of soil voids eliminates the surface tension between soil particles or aggregates and thus their cohesion.

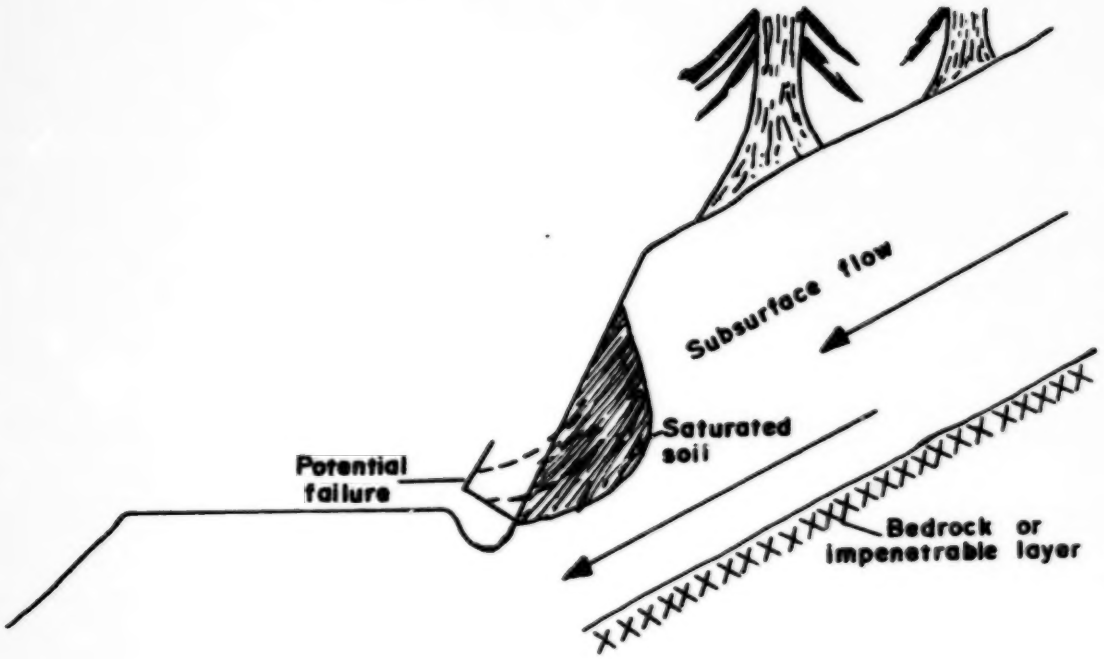
b. The water increases the weight of the unsupported cutbank (frequently cutslopes are steeper than the angle of repose of the soil and hence initially unstable).

c. The rise of the piezometric or groundwater surface causes an increase in the porewater pressure and results in a decrease in the shearing resistance of the soil (e.g. similar to the action of an hydraulic jack).

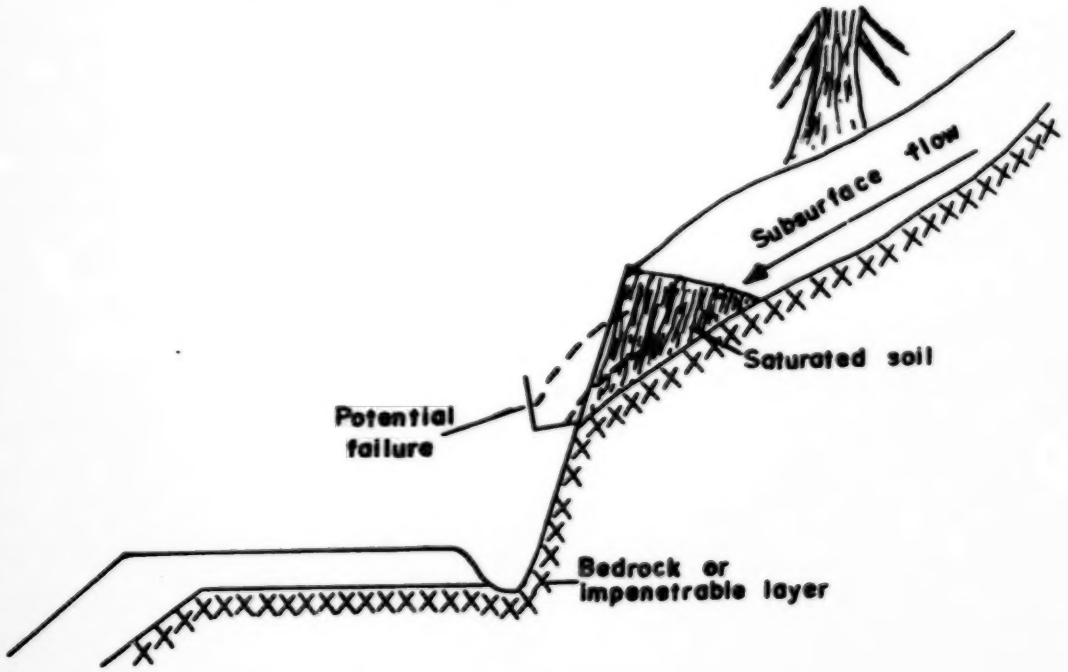
(Terzaghi, 1950)

Where soils are shallow to bedrock, to an impenetrable layer, or to where bedrock has been exposed by the road cutbank, the problem of instability through a saturated soil condition is magnified (Figure 2).

Cutbank failure due to a saturated soil condition may occur within the first year of construction or may take a number of years to occur. If failure occurs while the road is operational, operating time is lost through reconstruction efforts. Failure within a number of years may destroy regeneration on the road surfaces as well as on and above the cutbank. If a site has a high road density, such as produced by skidder yarding on steep slopes, the long term disturbance to the growing site may upset the expected rotation length and thus the sustained yield of the site. Regardless of the timing, cutbank failures usually fill in drainage ditches and produce sediment sources which inevitably find their way to stream channels (Dyrness, 1967a; Swanston, 1971).



a. Interception of subsurface flow in deep soils.



b. Interception of subsurface flow in shallow soils.

Figure 2. Interception of subsurface flow, saturation of soil and potential cutbank failure.

Subsurface water flows at a relatively slow velocity. The soil texture and structure, and the presence of macropores (e.g. root channels and animal burrows) determines the conductivity, but generally the velocity is in the order of metres per day. After interception by the road cut bank and the change from soil to surface water, the water is no longer constrained by the soil matrix, only by the channel (e.g. road surface or ditch). Velocity in open channels is in the order of metres per second - an increase in velocity by three orders of magnitude. This increase in velocity has several effects:

a. The ability of flowing water to detach soil particles is proportional to its kinetic energy (K.E. = $1/2\ mv^2$), and its competence or ability to move particles is proportional to the sixth power of the velocity. Since velocity increases by 10^3, kinetic energy increases by 10^6, and competence by 10^{36}. Thus interception of subsurface flow greatly increases the erosive power of the water, and

b. Water which previously flowed slowly through the soil to arrive at stream channels now short circuits part of the soil system and flows rapidly to stream channels. This decreases the stream response time* and increases the flood peaks. Since there is less water stored in the soil, low flows which depend on seepage may be made even lower.

As noted previously, subsurface flows maintain the water and nutrient supply to downslope vegetation. The effect on site index caused by the interception of subsurface flows has not received the intensive study which it perhaps deserves. Since sustained yield forestry endeavors to maintain or enhande site productivity, any action which has the possibility of reducing site productivity deserves very close scrutiny. On sites which experience moisture stress, the interception of upslope subsurface flows can be expected to increase the moisture stress and thus reduce the site productivity.

2. Ponding and diversion of surface flow

The recognition of surface flows depends upon the time of year that road reconnaissance, layout and construction are carried out. For example, during dry periods ephemeral and perennial streams may lack or have flows of only fractions of a cubic metre per minute. Unless

* streams become more "flashy" or quick to respond to precipitation input.

the peak flow potentials are recognized, road construction can lead to the filling in of the stream channels or the installation of culverts of inadequate size or design to handle flow. If this is the case, ponding and diversion of surface flows results.

Ponding of water above the road leads to seepage through the fill and an increase in the pore water pressures. This situation can result in road fill failures and short but serious soil flows (Swanston, 1971). Ponding, if extensive or prolonged, can also lead to a reduction in site productivity.

Diverted surface flows can follow one, or all, of three routes: into ditches; across the road surface; or down the road surface. Water diverted into ditches frequently over-taxes them and lowers culverts. Water diverted across road surfaces frequently results in gully erosion with the stream attempting to regain its previous stream gradient. Water diverted down road surfaces leads to fill erosion and subsequent gullying of the road. All three routes result in unnecessary erosion, road damage and water quality deterioration.

In some cases the culverts or bridges which are installed divert runoff into new courses. A number of situations can develop as the diverted stream cuts a new channel:

a. Growing sites are disturbed or destroyed through soil erosion, soil and debris deposition, or an excess of moisture. Along the old channel, growing sites may suffer due to a lack of moisture.

b. The additional water on some sites can initiate slope failure through increased pore water pressures, weight, and reduced root strength - the excess water killing or severely damaging the forest stand.

c. If the diverted stream emerges downslope at another road, the excess water with its suspended and bedload materials may overtax ditches and culverts, leading to further erosion, site disturbance, and water quality degradation.

d. The channel cutting and various other site and road disturbances can lead to water quality degradation for an extended period.

3. Reduction of infiltration capacity

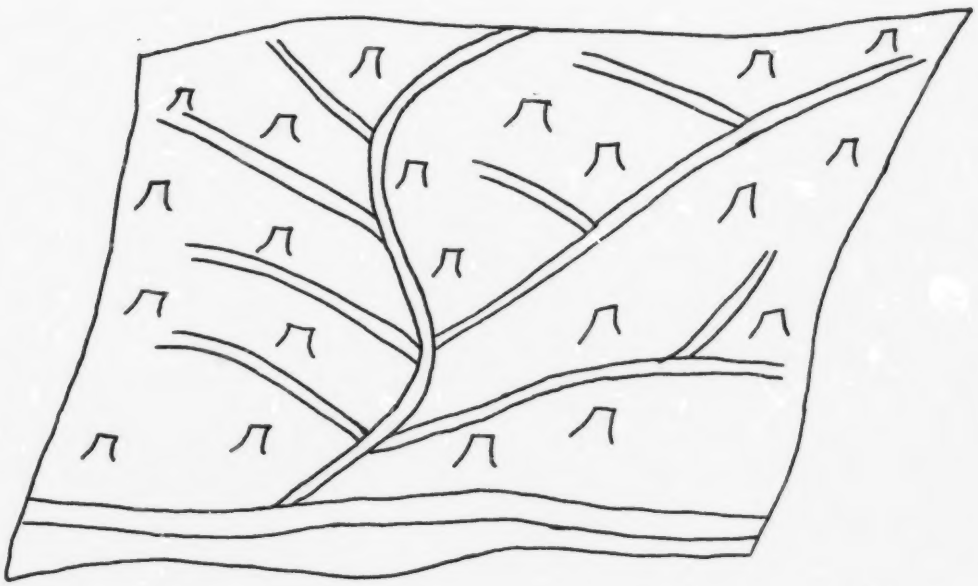
Construction of forest roads requires the removal of organic matter, mineral soil exposure, and soil compaction. These activities reduce the infiltration capacity of the soil on the road surface and enhance overland flow.

The impact on a site is proportional to both the area disturbed by roads and the layout of the roads. Skidder yarding necessitates a higher road density than high lead yarding. Regardless of the yarding method, planning of road systems reduces both road density and haphazard layout. Road layout is important since roads intercept and channel water (Figure 3). Roads, in fact, become new stream channels unless precautions are taken - avoiding long continuous grades, grades in excess of 25 to 30%, the construction of ditches and waterbars, installation of culverts, revegetation and maintenance. (Packer and Christensen, 1964; Rothwell, 1971). Where these precautions are not taken, erosion and gullying results (Photo 1).

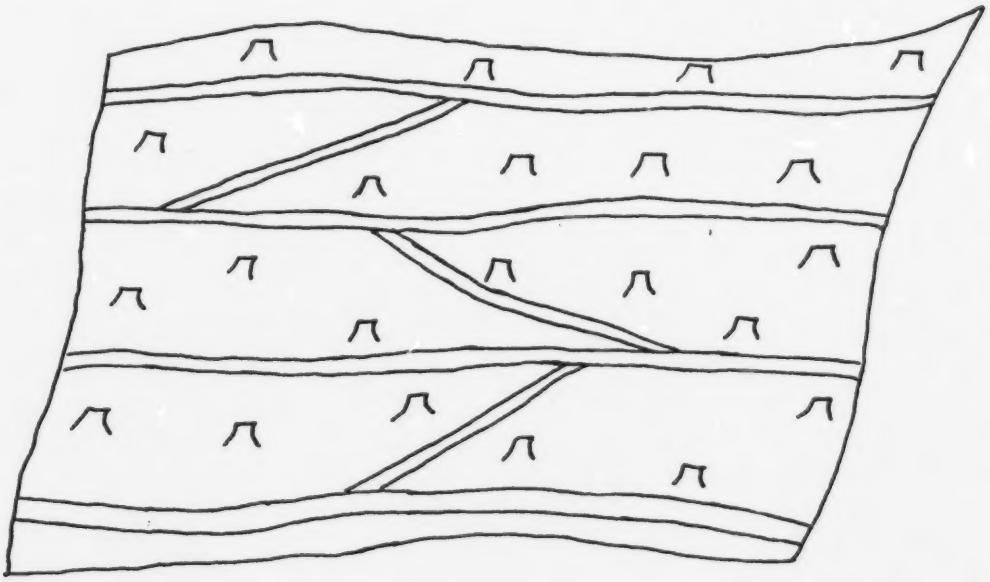
With reduced infiltration, the amount of water entering the soil is also reduced. This situation results in site deterioration because less moisture is available for plant growth (Silen and Gratkowski, 1953). Where surface erosion has occurred, the removal of the fine textured soil results in a reduced cation exchange capacity, and the presence of an erosion pavement, making the site even more harsh for the re-establishment of vegetation.

4. Lack of vegetation on road cut and fill slopes

With the lack of vegetation on cut and fill slopes, raindrop erosion breaks down soil aggregates. The liberated fine textured soil particles clog soil pores and reduce the infiltration capacity. This situation leads to overland flow and surface erosion. Although surface erosion is not as spectacular as mass soil erosion, it is nevertheless a very active agent in the erosion process. Dyrness (1970) noted that "in order to fully appreciate the magnitude of soil loss through surface erosion, one had only to realize that the loss of one inch of soil over an acre is roughly equivalent to 100 tons."



a. Roads which have a dendritic pattern concentrate runoff and increase erosion.



b. Roads which follow the contour result in less concentration of runoff and thus less erosion.

Figure 3. Road layout and concentration of runoff.

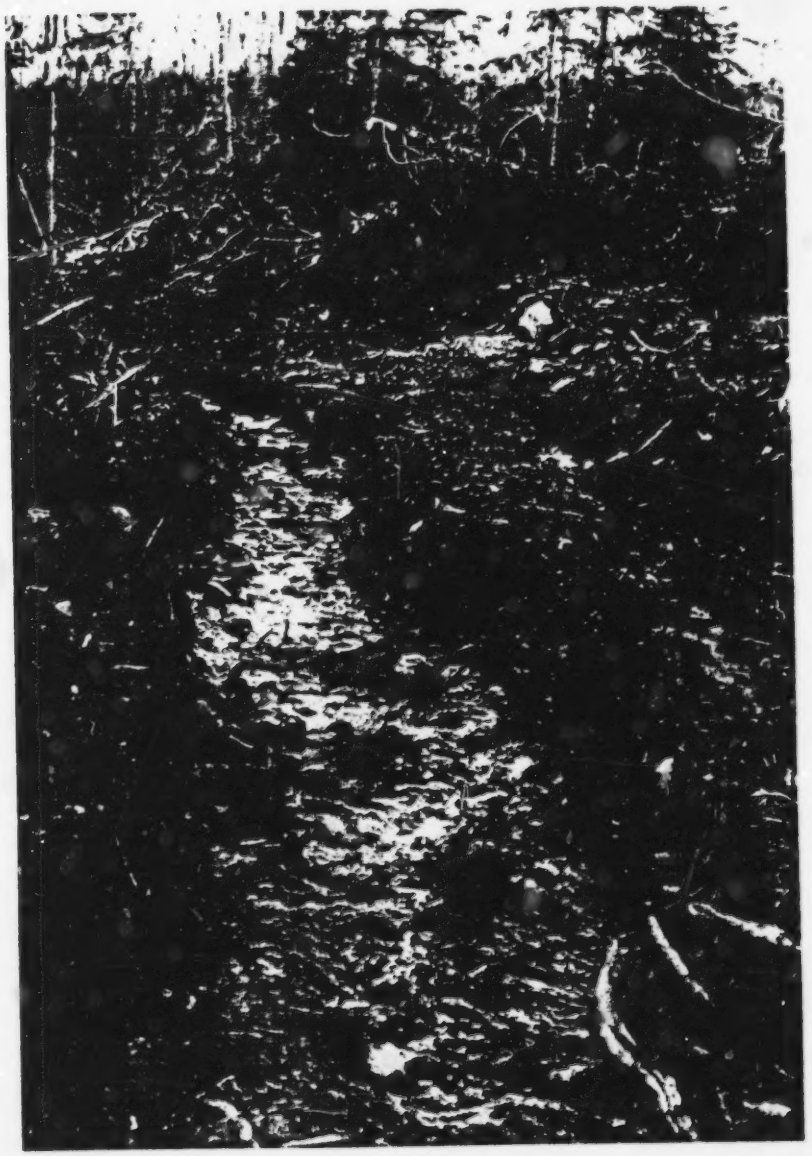


Photo 1. Where precautions are not taken, roads become new stream channels. When this occurs the hydrologic impact of roads is greatly increased and their utility is substantially reduced.

A forest road can disturb anything from 0.5 to 3 hectares per kilometre. If the surface erosion is only a portion of a centimetre over this area, soil movement can be very substantial.

Soil eroded from cut and fill banks either finds its way into ditches and stream channels, or moves downslope, frequently disturbing regeneration.

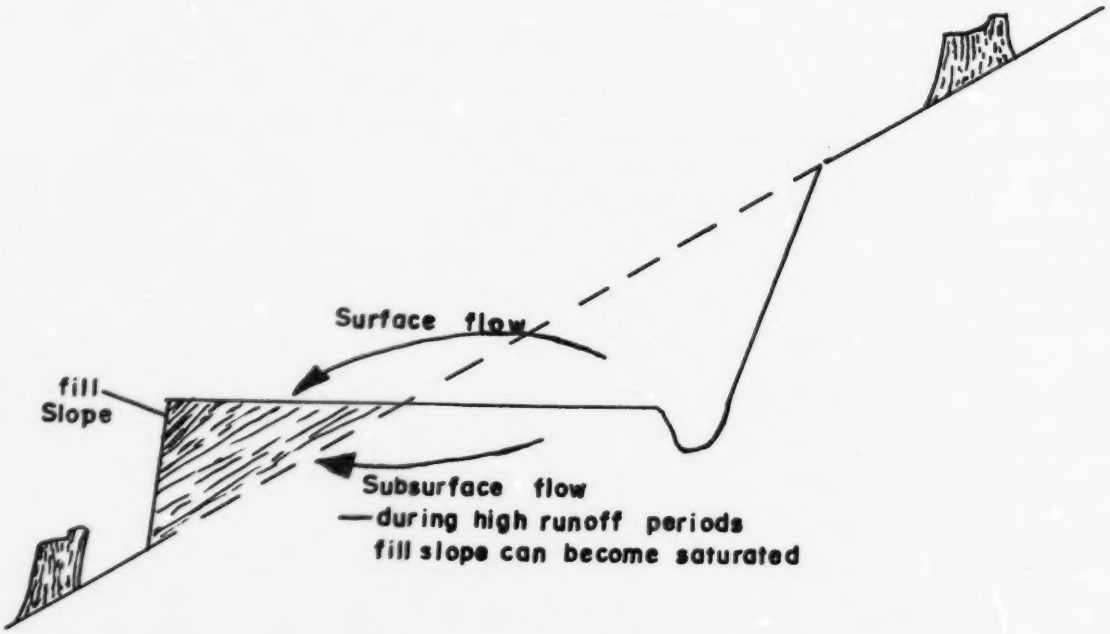
In addition to causing surface erosion, the water which fails to infiltrate the cut slope adds to the flow in the "road stream system".

Rapid revegetation of cut and fill slopes, either natural or seeded, ensures that infiltration is increased and surface erosion is reduced. Frequently, however, the deleterious effects of surface erosion are not recognized and the disturbed sites are left to revegetate slowly.

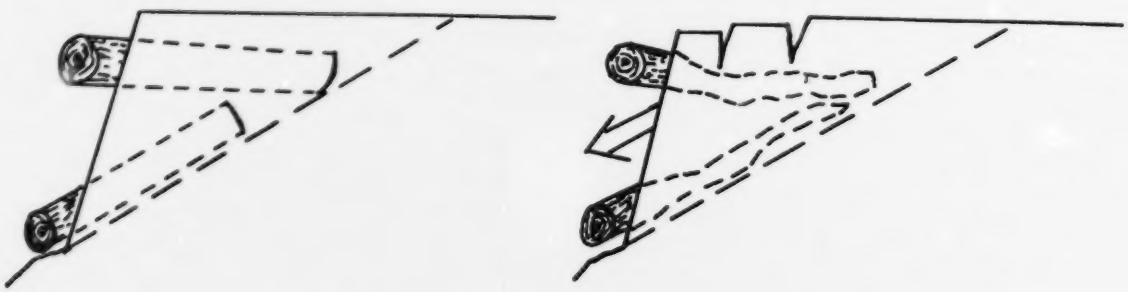
5. Side casting

The construction of roads in mountainous terrain usually necessitates the side casting of soil in order to achieve the required road width (Figure 4). In order to have the necessary slope bonding, shear resistance, and embankment density for maximum stability, it is necessary to remove organic debris before construction and to ensure that no debris is incorporated within the embankment (Larse, 1971). Frequently, however, there is organic debris underlying, supporting, or mixed with the side cast soil. This material is a common cause of road failure and mass soil movement.

Where natural slopes are at or near their angle of repose, the addition of side cast materials steepen and may overload the slopes. Obstructed upslope drainage creates saturated conditions in and above the road fill during periods of high runoff. These conditions frequently result in serious slumps and short but destructive soil flows (Swanston, 1971).



a. Cross section of road showing side cast fill slope and water movement.



b. Incorporation of organic matter in fill slopes is a poor road construction practice.

c. As the organic matter rots, the fill settles and tension cracks develop. Saturated conditions increase the instability.

Figure 4. Cross section of side cast fill slopes.

Tension cracks along the outer edges of road surfaces are an indication of instability and movement of side cast material (Photo 2).

When side cast materials fail, disturbance to growing sites below roads results. This not only affects the rate of regeneration, but where erosion is serious may determine whether regeneration will occur at all. The time element of disturbance is determined either by the rate of revegetation which aids in stabilizing the fill slope, or by the time span over which the slope requires to gain its angle of repose. Where slope stability relies on the fine roots of trees, any prolonged disturbance following logging which hinders regeneration may result in the initiation of mass soil movements. This aspect of slope stability is discussed in the next section.

Throughout the period of disturbance surface erosion results in the production of sediment which frequently leads to a degradation of water quality and aquatic environments.

6. Summary

Forest roads are a necessary part of forest management. Their construction requires a substantial capital outlay. In order to protect this investment and reduce the hydrologic impact, careful location, sound engineering, good supervision during construction, rapid revegetation of disturbed soil, and frequent maintenance inspections are necessary.

B. Forest Harvesting

On a given site, forest harvesting entails primarily two steps - modification of the forest canopy and yarding of the felled timber.

1. Modification of the forest canopy

Although there are many silvicultural systems applicable to forest harvesting (Troup, 1928), the most commonly used in the old growth coniferous stands of British Columbia is the clearcut system. The complete removal of the forest cover from a site has a number of hydrologic effects: a reduction of evapotranspiration; modification of snow accumulation; and, a possible reduction of slope stability.

Photo 2. Tension cracks in the road surface indicate instability and movement of side cast materials.

a. Evapotranspiration is the sum of three major components: $E_t = T + I_t + E_{s+w}$, where T is transpirational loss, I_t is total interception loss, and E_{s+w} is evaporation from all soil, rock and water surfaces not included under the other terms (Hewlett and Nutter, 1969).

In forested areas the evapotranspirational water loss is estimated at between 45 to 53 cm (Thornthwaite and Mather, 1957). However, this demand for water is not always in synchrony with supply (Figure 5). This requires a withdrawal of the soil water (Figure 6). When transpiring vegetation is removed, the reduction in soil water is much less - only the E_{s+w} factor - and this is limited to the top 30 cm or less (Herring, 1970; Rothacher, 1971; Troendle, 1970).

In depressional areas the removal of the biological "water pump" may result in a rise of the ground water table (Bay, 1967; Jarvis et al., 1966; Lutz, 1956; Trousdell and Hoover, 1955; Wilde et al., 1953). The rise in water table may be sufficient to preclude or seriously delay the re-establishment of tree cover (Jeffrey, 1968). For this reason heavy cutting (e.g. clearcutting) on depressional or receiving sites with poorly drained soils should be avoided. Where such cutting is unavoidable it may be possible to construct drainage ditches in order to overcome the high water table problem (Stanek, 1968). The term "paludification" is used to describe the situation where the ground water table has come to the surface and formed a marsh.

With the reduction of evapotranspiration and the higher soil water content on a site, less additional water than previously is required to incease subsurface and surface flows. As a result, unanticipated overloading of road drainage structures may occur in runoff periods (e.g. following spring and fall storms) (Wilde et al., 1953). This situation compounds the problem of interception of subsurface flows by road cut banks.

The question of additional soil weight, increased pore water pressure, decreased soil shear strength, and slope stability due to an increase in soil water content is discussed in the section on slope stability.

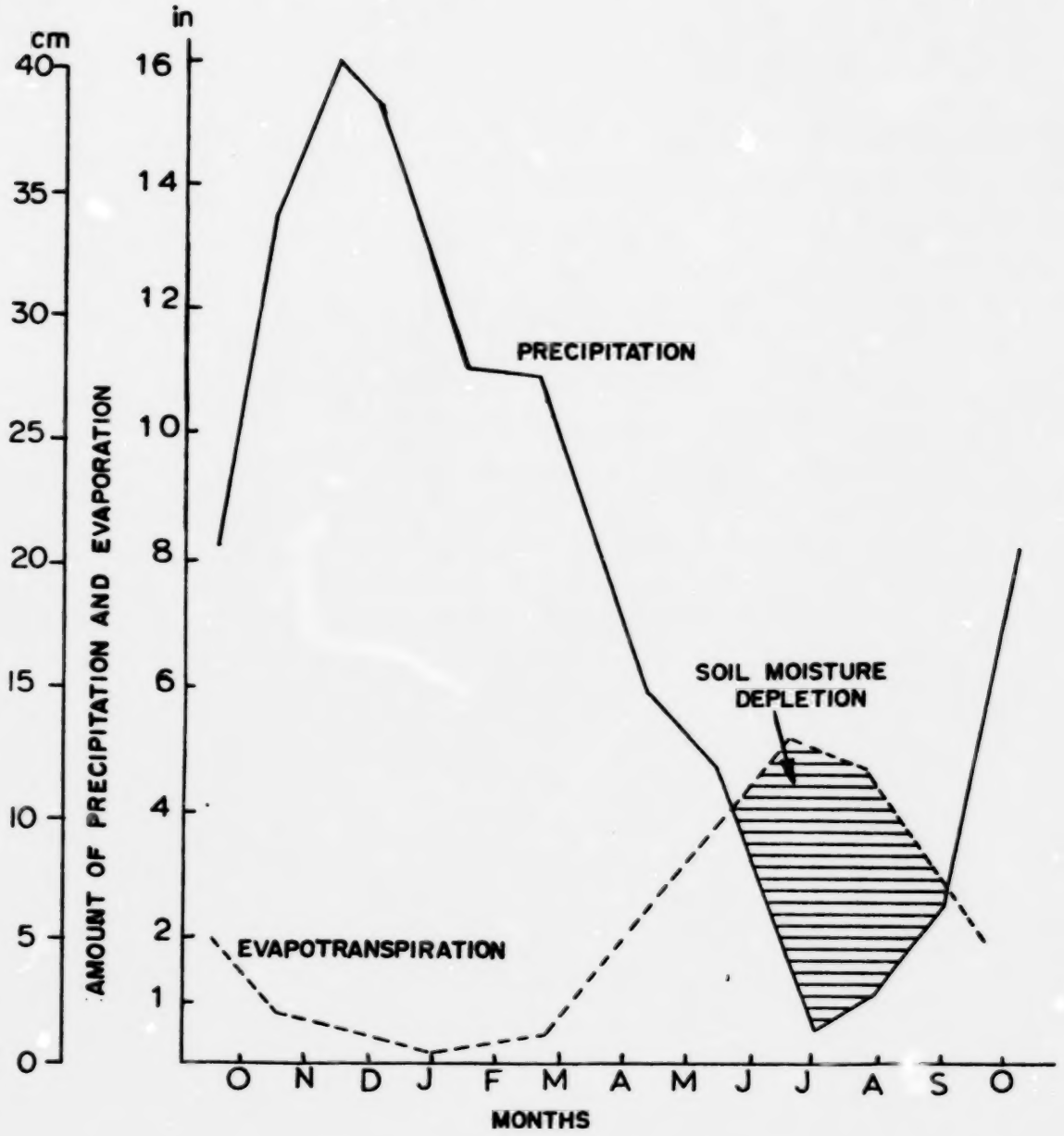


Figure 5. Mean monthly precipitation and evapotranspiration for the H.J. Andrews Experimental Forest. (Source - Rothacher, 1971).

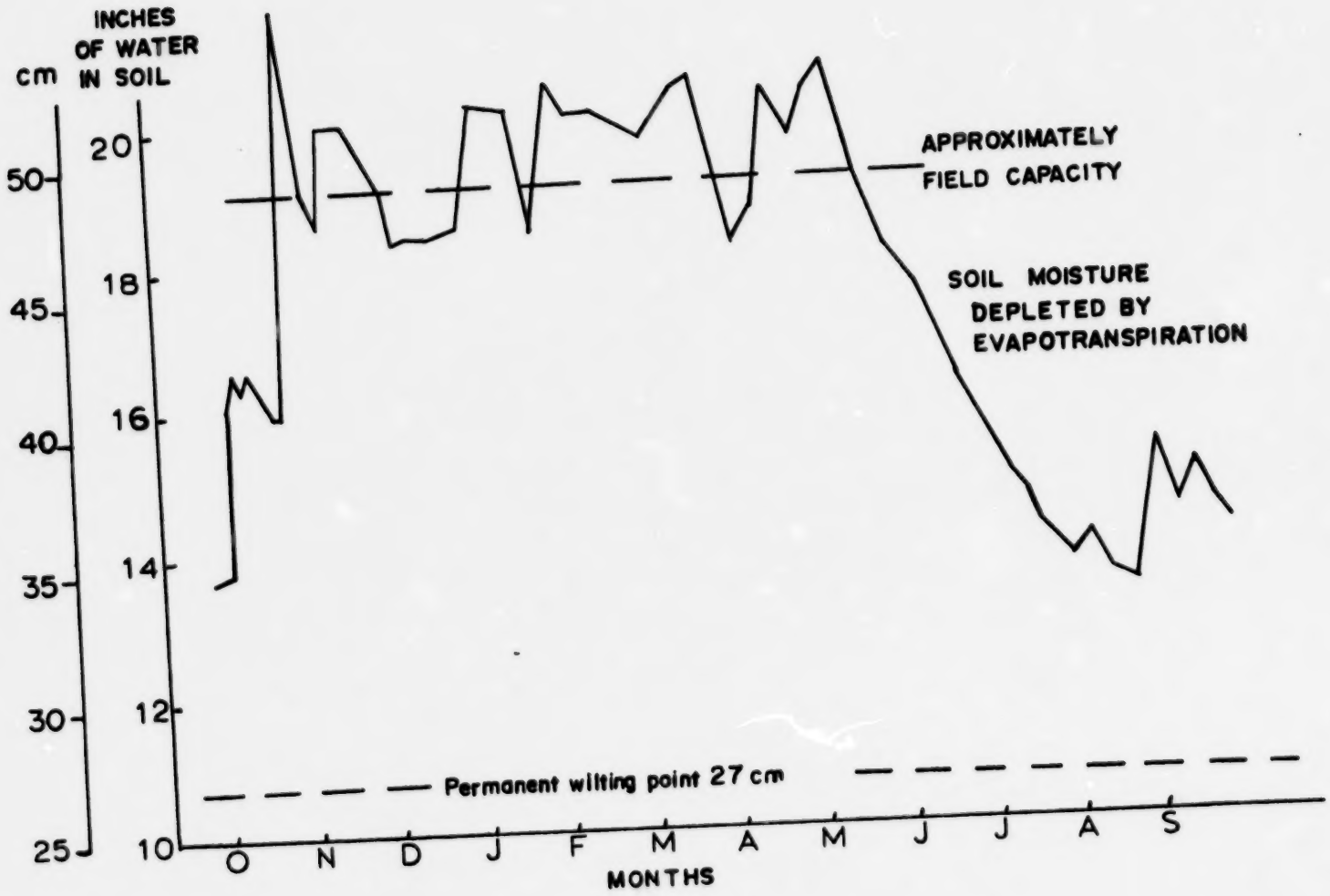


Figure 6. Annual soil moisture changes in the 0 to 4 foot depth (0 to 1.2 m) under old growth Douglas-fir. (Source - Rothacher, 1971).

Although the soil moisture levels are higher on a site, the water may not necessarily be available for transpiration. An example is during the winter when the soil is frozen. If snow* or another form of cover is not sufficient to shade regeneration from solar radiation or advective heating, the vegetation may begin to transpire. This situation, where water is lost from a plant and none is available to be taken back up, leads to a loss of vigor or death. These circumstances are less likely to develop under full or partial forest cover since both the energy input and depth of soil freezing are less (Sartz, 1973).

As the site becomes reoccupied by vegetation, the previous soil water regime returns. This recovery period is related to the biogeoclimatic zone and regeneration success, but varies between 15 and 40 years (Embry, 1971; Hallin, 1968; Orr, 1968; Tiesrin et al., 1935; Willington, 1975).

b. Snow accumulation and melt

Modifying the forest canopy through thinning or clearcutting influences the magnitude of snow accumulaton and its rate of melt (Anderson, 1970; Berndt, 1965; Gary, 1974; Hoover and Leaf, 1967; Miner and Trappe, 1957; Niederhof and Dunford, 1942; Wilm and Dunford, 1948). For many years the increase in snow accumulation was attributed to the reduction of canopy interception loss (Goodell, 1952; Goodell and Wilm, 1955). However during the late 1950's the conventional emphasis upon the interception theory was seriously questioned (Hoover, 1960). Goodell (1963) cited two reasons for this change in thought: (1) the lack of energy available to vaporize substantial quantities of snow, and (2) the possibility that the techniques used to compare snow

* Although snow depths are generally greater in a clearcut than under the forest canopy, wind drifting may lead to bare areas within the clearcut.

accumulation on forested areas and adjacent openings could be biased due to differential snow distribution rather than interception loss. Subsequent studies have found that snow redistribution is the primary reason for increased snow accumulations in clearings (Gary, 1974; Hoover and Leaf, 1967). Thus the increases are largely offset by decreases in snow accumulation beneath the forest canopy downwind (Figure 7).

For the optimum snow accumulation, openings should be protected from wind, be round or patch-shaped, and have diameters that do not exceed five to eight times the height of the surrounding forests (Hoover, 1969). Using this guide, opening size would vary from 1.2 to 6 hectares. Generally, in British Columbia clearcut openings range from 16 to 80 hectares. For this reason, less than optimum snow accumulation would result due to snowpack scouring by wind eddies (Leaf, 1975).

The additional snow accumulation in openings in terms of water equivalent can be 30 to 40% higher than the snowpack on the adjacent forested site (Gary, 1974; Hoover and Leaf, 1967; Wilm and Dunford, 1948). Where the canopy is modified through partial cuttings, the increase in snowpack is proportional to the amount cut (if clearcutting increases the snowpack by 30% - cutting half the trees increases the pack by 15%) (Hoover, 1960). Thus, in addition to increased soil moisture levels due to reduced evapotranspiration, canopy removal results in additional site moisture due to redistribution of snow.

The initial interest in canopy modification and snow accumulation was due to the hypothesis that delayed snowmelt could be induced through increased accumulations. However, Rothacher (1965) noted that there are no indications that snow will persist longer in any practical width strip than it would under shade of the forest. In fact, Leaf (1975) noted that on all aspects, snowmelt in clearcut openings is more rapid than in the uncut forest. The increased melt rate is partially offset by the higher snow accumulations, and as a result snow disappears from openings and uncut forest areas at approximately the same time (Wilm and Dunford, 1948). However, in the large canopy openings created by harvesting in British Columiba, rapid snowmelt due to exposure may result in much earlier snowpack disappearance than on uncut forest areas.

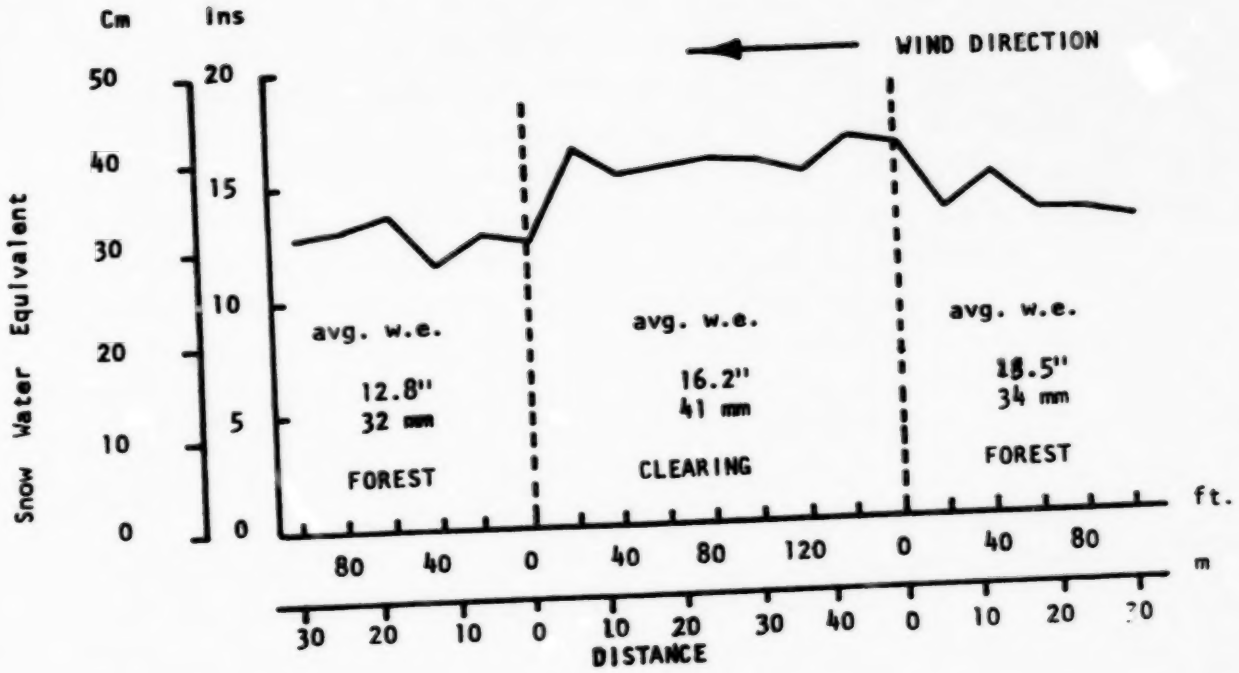


Figure 7. Redistribution of snow leads to an increase in snow water equivalent in clearings and a decrease in snow water equivalent beneath the forest canopy downwind. (Source: Gary, 1974).

In general, melt rates appear to be similar on both east and west aspects at all elevations, but melt rates are higher on south aspects than north, although this difference decreases with elevation (Bates and Henry, 1928; Garstka et al., 1958; Gary and Coltharp, 1967; Leaf, 1971).

The duration of the hydrologic impact depends on the persistence of the effects of canopy modification on (1) the snowpack accumulation and melt, and (2) soil moisture depletion and other evaporative losses (Anderson, 1970). The duration of effect on snow accumulation can be substantial with Hoover and Leaf (1967) reporting measureable effects after 28 years, in spite of vigorous regeneration and increased canopy density. The effect on soil moisture decreases rapidly due to revegetation of the site. A range of 4 to 16 years has been reported (Anderson, 1963; Siemer, 1964).

c. Slope stability

Slope stability is determined by the balance of forces tending to move the slope and those resisting movement. This balance of forces can be conceptualized using the soil mechanics formula:

$$\text{Safety factor} = \frac{\text{Shear stress}}{\text{Shear strength}}$$

The components of shear stress include the slope angle and the weight of the slope - soil, trees and water. The components of shear strength include the cohesive strength of the soil, strength contributed by root systems and the strength contributed by friction. When the safety factor is less than 1.0 the slope is stable. When the factor is equal to or greater than 1.0 the slope is unstable.

Soil mechanics theory has been applied to slope stability analysis (Ballard and Willington, 1975; Gray, 1969; Terzaghi, 1950). However its application is difficult due to the heterogeneous nature of the soil materials, the extreme variability of soil water conditions and the related stress-strain relationships with time (Swanston, 1971). For this reason most studies on slope stability have been largely observational in their approach to determining the critical combination of hydrologic, slope, soil, and geologic conditions that lead to instability.

Numerous studies have been conducted in the mountainous terrain of western North America - Ballard and Willington (1975) in the Chilliwack River Valley, B.C.; Bishop and Stevens (1964) in Alaska; Corbett (1966) in California; Croft and Adams (1950) in Utah; Dyrness (1967a) in Oregon; O'Loughlin (1972) in southwestern British Columbia; Swanston (1969) in Alaska; and, Utzig and Herring (1974) in British Columbia. These studies yield a broad regional perspective on the critical combination of site factors which favour slope instability:

(1) Natural - slopes between 30-40^{o} (60-80%)
- noncohesive soils (low clay content)
- steeply sloping planes of weakness along smooth bedrock (glaciated or tilted sedimentary) or basal till provide little mechanical support to the slope soils, and also create avenues for concentrated subsurface flow and active pore water pressure development.
- intense precipitation (12-15 cm/24 hrs) which drastically increases pore water pressures
- topography which collects surface and subsurface drainage (drainage depressions, seepage hollows, deeply incised or V-notch ravines, or steep stream channels) or poorly drained open slopes
- active rockfalls which lead to the sudden loading of slopes, thereby initiating slope failure
- areas of high seismic activity
- areas subject to high winds.

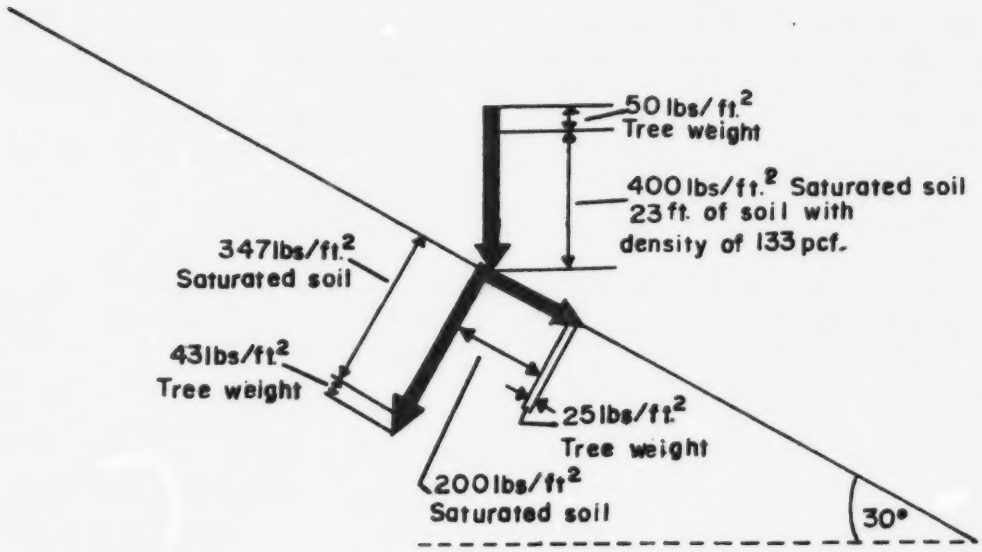
(ii) Man Made - forest harvesting (clearcutting) or stand damage (slashfire escapes, blasting or sidecasting during road construction, yarding)
- soil disturbance, road and landing construction, yarding.

While soil mass movements - the downslope movement of soil primarily under the influence of gravity - occur on undisturbed slopes, both road construction and clearcutting increase the frequency of slope failures. The impact of forest roads on slope stability was discussed in previous sections. In order to appreciate the impact of clearcutting on slope stability, it is necessary to outline the stabilizing role of forests. They influence slope stability in four ways: (after Gray, 1969)

(i) Mechanical reinforcement from the roots has been suggested as the most important effect of trees on slope stability (Bishop and Stevens, 1964; Corbett, 1966; Croft and Adams, 1950; Dyrness, 1967a; O'Loughlin, 1972). Swanston (1974) noted four possible roles which roots could play - anchor the soil mantle to the substrate, provide a continuous long fiber adhesive binder to the entire slope soil mass, tie the slope together across zones of weakness and instability to more stable soil masses, and provide downslope support to an unstable soil mass through buttressing.

(ii) Modification of soil moisture distribution by transpiration was discussed in the previous section. The depletion of soil moisture through transpiration produces negative pore water pressure (or suction) which is conducive to slope stability. A forest can also intercept moisture either in the canopy or in the forest floor (e.g. part of the evapotranspirational water loss).

(iii) Surcharge or the added weight of the forest would appear to decrease slope stability, however there is an accompanying increase in slope stability (Figure 8). The significance of the surcharge is rather low. Bishop and Stevens (1964) estimated the weight of a spruce-hemlock forest to be 50 psf. (2400 Pa) or the equivalent of a layer of soil 15 cm thick.



N.B. 1 pound-force per square foot = 48 pascals
1 pound per cubic foot = 16 kilograms per cubic metre

Figure 8.

A vector diagram showing the effect of a tree on slope stability.

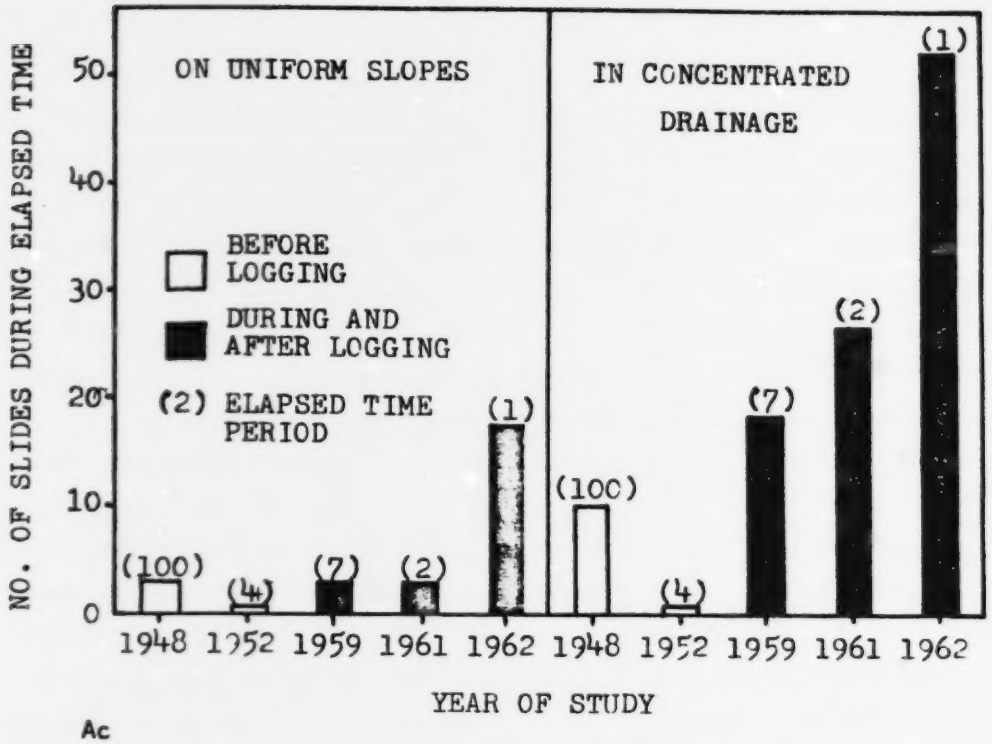
The additional downhill or shearing force due to tree weight is less than the additional normal force. Thus the surcharge or weight added to a slope by a tree increases slope shearing strength and thus stability.

(Gray, 1969).

(iv) Windthrow creates localized disturbances in the soil mantle. It normally affects overmature and diseased trees which are not affording a great amount of either mechanical reinforcement or transpirational moisture loss. However, Swanston (1969) noted that the direct destruction of stabilizing root masses through windthrow during periods of high pore water pressure can cause failure of steep slopes ($40\text{-}60^{\circ}$) with coarse textured cohesionless soils. While Gray (1969) stated that the dynamic loading of the soil mass by wind forces acting on the tree cover had not been evaluated, field observations by Swanston (1969) indicate that it can be a factor in the initiation of slope failure. Apparently the effect of root wedging or the tendency of roots to penetrate soil and rock, thereby loosening it up or opening cracks and fissures, is unknown (Gray, 1969). It is assumed however that the beneficial effects of root systems on slope stability far outweigh any possible adverse effects.

Following clearcutting there is an immediate reduction in evapotranspiration. As noted in the previous section this leads to an increase in the soil moisture and a possible rise in the ground water level. Therefore, when storm events or snow melts occur, less moisture is needed to saturate the soil. With saturation, the pore water pressure increases and results in a decrease in the shearing resistence of the soil. Immediately following clearcutting the effect of the reduced shearing resistence may not lead to slope instability. This is due to the mechanical reinforcement of the soil by the root systems. However, O'Loughlin (1972) noted that within four to five years the root systems will have lost a significant proportion of their tensile strength, and this plus the increase in pore water pressure leads to slope instability.

A number of studies have attributed an increase in slope instability and mass soil movement to clearcutting (Ballard and Willington, 1975; Bishop and Stevens, 1964; Corbett, 1966; Croft and Adams, 1950; Dyrness, 1967a; and, Swanston, 1969). As an example, Bishop and Stevens (1964) noted a tremendous increase in both the frequency of slides and the area affected after logging. Their observations are presented in Figure 9. They attributed the destruction of interconnected root systems and their gradual deterioration to the accelerated frequency of slides. They cite the time lag in slide activity after logging to support this view.



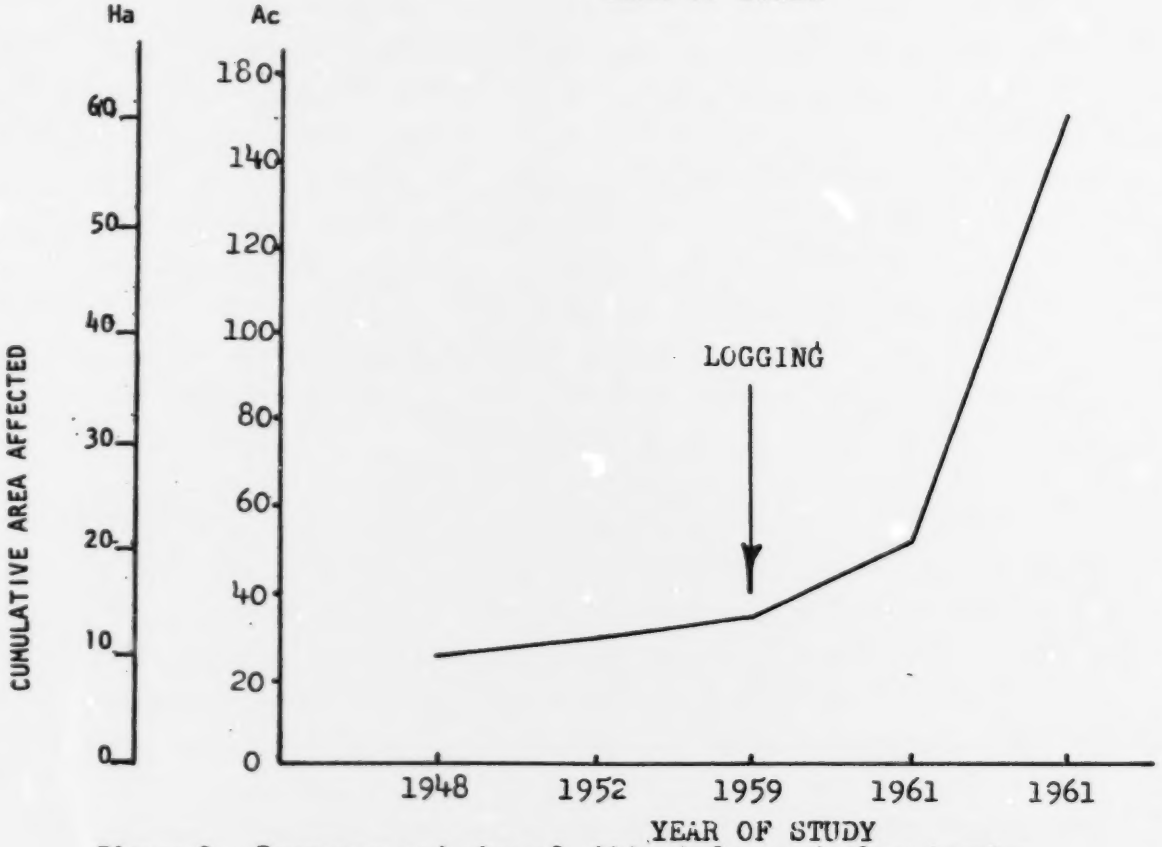


Figure 9. Frequency and size of slides before and after logging in Maybeso Creek, Hollis, Alaska (after Bishop and Stevens, 1964).

In areas which are recognized as potentially unstable, management practices should focus on maintaining a thrifty forest cover through a selection or shelterwood silvicultural system. (See Troup (1928) for a discussion of these systems.) Yarding and hauling equipment should be very compact so that the required roads are narrow and thus have a very slight hydrologic impact on the slope. Road layout should be done on the ground during the period of highest runoff so all water courses can be observed. Construction should be carried out in the driest period and all water courses previously observed should be maintained in their channels through the use of culverts or dips in the road. The road surface should be outsloping to direct water downslope rather than channelling runoff, and should be revegetated with grass to reduce surface erosion.

The techniques and equipment developed in New Zealand provide an example for the management of sensitive forest sites. Cunningham (1967) discusses the use of small vehicles developed in the European Alps for earthmoving, dragging, winching, and transporting men. The "heavier" models, with four-wheel drive and 8 to 11 horsepower can carry loads of (3,000 pounds) at speeds up to (6 miles per hour) (Figure 10)*. The roads required for these vehicles are substantially smaller than conventional forest roads (Figure 11).

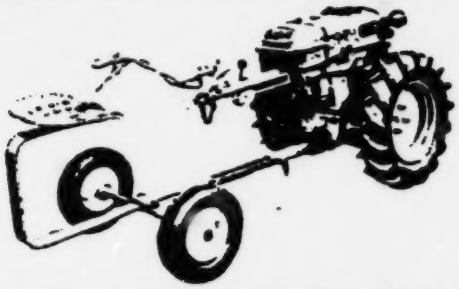
Even though extreme, this example illustrates the point that management of the forests does not require D-9 catepillars, 136 tonne trucks, or roads with 20 metre right-of-ways and 6 metre road surfaces.

2. Yarding of Felled Timber

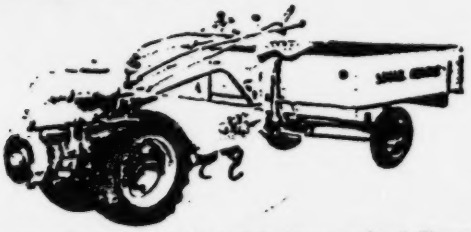
The second step of forest harvesting is yarding of the felled timber. A number of yarding systems have been developed, some having a major hydrologic impact on mountainous sites (e.g. skidder yarding on slopes over 30%), others having minimal impact (e.g. balloon yarding). The impact of a given yarding system can vary due to a number of factors - the site (slope angle, microtopography, slope position, soil parent material, and soil texture); preyarding planning (setting boundaries, landing location, skid road location); machine operator (experience, environmental

* 1 horsepower = 746 watts
1 pound = 0.45 kilograms
1 mile per hour = 1.6 kilometres per hour

(a) Heavy duty tractor and trailer. Payload 30 cwt. 4-wheel drive, articulated. Track width (trailer) 3 ft 11 in., wheelbase 12 ft 4 in. Diesel or petrol motor, 8 to 11 hp. Cost including trailer approximately $760.



(b) Tractor unit shown in (a). Can be used with or without operator's seat. Four forward and four reverse gears. Speed up to 10 mph. Cost of tractor unit approximately $500.



(c) Light tractor (8 h.p.) and trailer with 8 cwt payload. Front-wheel drive only. Track width (trailer) approximately 3 ft 6 in. Approximate costs: Tractor unit, $300. Trailer with foot and hand brakes, $120.

(d) A wide range of attachments is available. Those likely to be used in N.Z. protection forests are trailers ($100–$300), winches ($150–$250), blades ($50–$150).

N.B. 1 cwt = 45 kg 1 ft = 0.3 m

1 hp = 746 W 1 mph = 1.6 km/h

Figure 10. Some typical narrow width tractors and equipment used for managing New Zealand protection forest. (Approximate New Zealand costs from Cunningham, 1967).

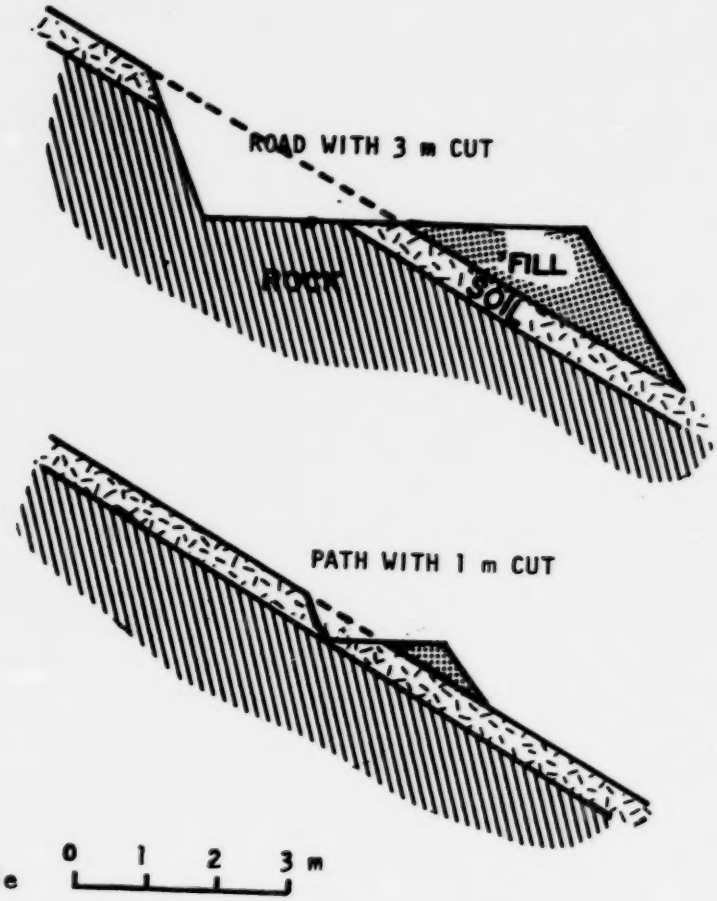


Figure 11. A diagram to illustrate the difference in earth work between a road with a 6 m surface (3 m cut) and a path with a 2 m surface (1 m cut). The path is designed for the protection vechicles shown in Figure 10. (Cunningham, 1967)

awareness, degree of supervision); soil moisture conditions (affects compaction and the soil disturbance from skidding machines); and, the season (whether snow or ground frost is present or absent).

Numerous studies have been conducted on soil surface conditions following the yarding of felled timber (Bockheim et al., 1975; Dyrness, 1965, 1967b, 1972; Garrison and Rummell, 1951; Klock, 1973; Megahan and Kidd, 1972; Ruth, 1967; Schwab, 1976; Smith, 1977; Steinbrenner and Gessel, 1955; Wooldridge, 1960). The results of several studies are summarized in Table 1. Basically five soil disturbance classes have been recognized:

(i) Undisturbed - no visible alteration of the forest floor by removal or addition of material and no compaction,

(ii) Forest Floor - is the disturbance of the forest floor (L-F-H) with no mineral soil exposed.

(iii) Shallow Disturbance - is the exposure of mineral soil and the removal and/or deposition of soil less than 5 cm in depth.

(iv) Deep Disturbance - is the removal and/or deposition of mineral soil to a depth greater than 5 cm.

(v) Compacted - obvious compaction due to the passage of a log, track, or wheel!

Apparently, slight disturbance has little effect on the physical-hydrological characteristics of the surface soil (Dyrness, 1965).* However, deep disturbance leads to exposure of the mineral soil to raindrop erosion. With the destruction of soil structure and the transport of soil particles, soil pores become plugged, decreasing the infiltration capacity. Compacted soils also have a reduced infiltration capacity.

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* For this reason Bockheim et al. (1975) concluded that exposed mineral soil was probably the most useful single index of harvesting disturbance, being meaningful in terms of erosion susceptibility and forest regeneration potential.

Percent Yarding Disturbance by Categories[a]

Investigator	Region	Logging Method	Forest floor	Shallow	Deep	Compact	Total	Mineral Soil Exposed
Garrison and Rummell (1951)	E. Ore. & Wash.	Horse (2)[b]	--	9.5	2.3	--	11.8	11.8
		Jammer (3)	--	13.3	1.9	--	15.2	15.2
		Tractor (18)	--	5.8	15.0	--	20.9	20.9
Wooldridge (1960)	N. Cent. Wash.	Tractor (1)	7.2	6.3	15.9	--	29.4	22.2
		Skyline (1) Crane	5.2	2.2	3.2	--	11.1	5.4
Dyrness (1965)	S. Cent. Wash.	Tractor (1)	--	26.4	8.9	26.8	62.1	35.3
		Highlead (3)	--	21.5	9.7	9.1	40.3	14.1
Dyrness (1967b)	C. Ore.	Wyssen Skyline (1)		24.4	4.7	3.4	32.5	12.1
Ruth (1967)	W. Ore.	Highlead (4)	--	--	--	--	15.8	15.8
		Skyline (4)	--	--	--	--	6.4	6.4
Dyrness (1972)	C. Ore.	Balloon (2)	--	15.8	2.6	1.7	20.1	6.0
Bockheim et al. (1975)	Coastal B.C.	Tractor (2)	18	11	58	--	87	69
		Highlead (1)	30	18	11	--	59	29
		Helicopter (1)	31	2	3	--	36	5
Schwab (1976)	Quesnel Highlands B.C.	Tractor (11)	7.9	4.7	39.4	--	52.0	44.1
		Running Skyline (4)	7.4	4.1	5.4	--	16.9[d]	9.5
Smith and Wass (1976)	E. & W. Kootenay B.C.	Tractor (67)[c]	2.9	7.1	23.3	--	33.3	30.4
		Highlead (14)[c]	2.7	6.5	7.5	--	16.6	14.0
		Grapple (2)[c]	6.6	2.9	22.5	--	32.0	25.4[e]
		Jammer (2)[c]	0.1	4.7	3.0	--	7.8	7.7
		Skyline (1)	6.7	6.3	1.3	--	14.3	7.6

Table 1. Summary of Soil Disturbance Studies in Mountainous Areas of The Pacific Northwest and B.C.

a. Percentages are from published data or calculated from published data.
b. Number of sites examined.
c. Sites examined are subdivided by transect segments.
d. With tailspar and perimeter access roads (4.3%), and yarder and skidder roads (4.3%), total yarding disturbance would equal 25.5%.
e. Grapple yarding undertaken by inexperienced crew.

Willington (1969) noted that generally those areas in the deeply disturbed and compacted classes occur as small scattered patches, and may not contribute to significant run off and erosion in spite of reduced infiltration capacities. While this is generally true, it is important to consider two aspects of disturbance - the orientation (whether parallel or at right angles to the contour), and spatial expression (whether continuous or in patches). One type of disturbance, skid road, is frequently at right angles to the contour and thus represents a continuous channel to overland flow. The result can be significant erosion damage, particularly on shallow to bedrock soils.

As discussed in the first section, forest roads have a major hydrologic impact on a mountainous site. It is significant therefore to compare the road requirements of several yarding systems. For every kilometre of road required for the skyline system, approximately three kilometers are required for high lead, and ten kilometers for skidder yarding. (Binkley, 1965; Wooldridge, 1960). Yarding systems which require high road densities are unacceptable in many steep mountainous sites (Megahan and Kidd, 1972). While systems with lower road densities reduce the hydrologic impact, poor road construction can still pose a serious problem. The alternatives are:

(i) Ignore the hydrologic impact

(ii) Eliminate logging

(iii) Develop yarding systems that require fewer or smaller roads, and accept the responsibility and cost of properly locating, constructing and maintaining roads.

(Megahan and Kidd, 1972).

3. Summary

Clearcut forest harvesting removes the canopy, thus reducing evapotranspiration and slope stability, and increasing snow accumulation and melt. Sensitive sites can be identified and either avoided or forest harvesting practices can be modified to reduce the hydrologic impact.

C. Silvicultural Site Treatments

Following harvesting the forest site is usually treated for several different purposes:

- reduction of fire hazard,
- preparation of suitable seed bed for regeneration,
- reduction of insect and/or disease hazard,
- to facilitate planting, and
- to remove competing vegetation.

A number of silvicultural treatments can be used - broadcast burning, spot burning, chipping, mechanical scarification, mechancial crushing, burying, and chemicals. The emphasis in this section is on broadcast burning since it is the most widely applied silvicultural site treatment in the mountainous areas of British Columbia (Feller, 1972).

1. Broadcast burning

The hydrologic effects of broadcast burning vary both within and between sites due to differences in fire intensity and duration which are controlled by the fuel (composition, arrangement, amount, moisture content), and the soil (texture, structure, organic matter content, depth, moisture content). In general, severe intensity* burns are hydrologically detrimental whereas light intensity burns have a range of effects from detrimental to beneficial (Feller, 1972). Since severe burns occur only beneath the heaviest concentrations of large fuels they are generally distributed in small, discontinuous patches occupying between 5 and 15%** of the total logged area (Tarrant, 1956; Dyrness et al., 1957).

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* A severe burn occurs where fire removes all the organic litter from the surface and in addition leaves the mineral soil highly coloured. A light burn occurs where fire chars the surface of the organic layer but does not remove it (Tarrant, 1956).

** These values are for sites which were approximately 50% unburned. If a burn is more extensive the area severely burned would be expected to be greater.

Broadcast burning modifies a number of site factors and thus hydrologic characteristics. In this section only the impact of burning itself is discussed. Site disturbance due to perimeter access trails is similar to skid road construction, and scarification for fire guards is similar to general scarification.

a. The removal of vegetation and organic matter

The major hydrologic impacts of vegetation removal - reduction in evapotranspiration, reduction in slope shear strength and snow redistribution - accompany forest harvesting. Broadcast burning, by increasing the removal of vegetation, logging slash, and soil organic matter, adds to the harvesting impact.

Removal of this protective organic material, plus logging disturbance expose the mineral soil to the compacting and pore plugging potential of rainfall (Willington, 1969). Added to this mechanical breakdown of soil particles is the chemical influence of the alkaline ash. An abundance of univalent cations can lead to a deflocculation of soil colloids and a disintegration of soil aggregates (Feller, 1972).

b. Infiltration

The mechanical and chemical processes discussed above lead to a reduction in soil porosity. Willington (1969) noted that there is a high correlation between soil porosity and infiltration rate. For this reason there is fairly consistent agreement in the literature regarding the detrimental effects of severe burns on infiltration. However, Willington (1969) observed that there is a variety and conflict of opinion and data regarding the effect of light burning on infiltration.

Scott and Burgy (1955) found that high heat (300°C) applied to soil increased infiltration through increasing aggregation and permeability in the surface layer (0 to 0.6 cm). The increased aggregation was attributed to fusion of clay particles. In a later paper, Scott (1956) qualified these findings and stated that caution should be used in the application of fire for the purpose of increasing infiltration.

He noted that such questions as the stability of the physical and chemical changes, the effect of raindrop impact, surface runoff effects, and the loss in vegetative cover and the resulting decrease in interception must be evaluated.

It is interesting to compare the laboratory results of Scott and Burgy (1955) with the results obtained in a field study by Dyrness et al. (1957). Aggregation was found to be reduced in severely burned soils due largely to the removal of colloidal organic matter by fire. Since many aggregates in surface soils depend on colloidal organic matter as their cementing agent, its loss leads to aggregate disintegration and thus a reduction in infiltration capacity. Although fusion of clay particles appeared to occur at high temperatures, Dyrness et al. (1957) found this process failed to offset the breakdown of naturally formed aggregates which was occurring simultaneously.

Increases in infiltration capacity following exposure of the mineral soil can occur in some cases due to increased frost heaving, decay of wood and enhanced revegetation (Feller, 1972). However these processes require at least one year or winter season to improve infiltration. During this time erosion resulting from reduced infiltration and exposed mineral soil may be visually imperceptible but still yield significant soil losses (Sartz, 1953).

Broadcast burning can influence the infiltration capacity by modifying the "wettability" of a soil. Non-wettable soils are termed hydrophobic and have a lower infiltration rate than wettable or hydrophilic soils. Some soils are naturally hydrophobic due to chemical compounds in the litter or due to leachates from the litter. Jamieson (1969) reported that broadcast burning increased infiltration capacity through the removal of hydrophobic litter. DeBano (1966) reported that broadcast burning reduced infiltration capacity through the downward movement of vapours containing hydrophobic compounds which condensed on soil particles to form a hydrophobic layer. These apparently conflicting views, can in part be explained.

The instrument to measure infiltration (infiltrometer) used by Jamieson (1969) extended into the soil only 0.6 cm. Following broadcast burning, measurements taken indicated that infiltration had increased. Two reasons for this were suggested: (1) vaporization of the hydrophobic compounds into the atmosphere, and (2) vaporization, downward diffusion and subsequent condensation of the hydrophobic compounds in the lower layers of the soil. Jamieson (1969) stated that his experiment was not designed to measure the atmospheric loss nor the formation of a hydrophobic layer. In fact, if a hydrophobic layer was present below the 0.6 cm layer it would not have been detected by his infiltrometer due to lateral flow. DeBano and Krammes (1966) found that following burning the hydrophobic compounds had diffused into the soil, leaving both the surface ash layer and the mineral soil layer for up to five cm, wettable or hydrophilic. However, the soil in the next five to 10 cm layer was hydrophobic. They found that it was this layer that inhibited infiltration.

The effect of a hydrophobic layer is a reduction in the infiltration rate during the early stages of moisture input, and a gradual increase with time. This is opposite to the normal infiltration rate which is initially high and then reduces to the percolation rate as the soil pores become filled (Figure 12).

Where mineral soil is exposed, soil freezing may affect infiltration rates. Since there are basically four classes of soil frost, their effects vary from increasing infiltration to reducing it completely. Granular frost consists of small frost crystals that aggregate around the soil particles. This improves soil aggregation and results in higher infiltration rates (Byrnes, 1961; Trimble et al., 1958). Stalactite frost consists of loosely fused vertical icicles that join heaved soil particles with the soil below. Stalactite frost promotes rapid absorption of snowmelt and prevents overland flow (Haupt, 1967). Honeycomb frost has a loose, porous structure and is generally found in highly aggregated soils. It usually reduces infiltration capacity and increases overland flow on burned or sparsely vegetated sites, but does not infiltration where plant and litter cover are appreciable (Haupt, 1967).

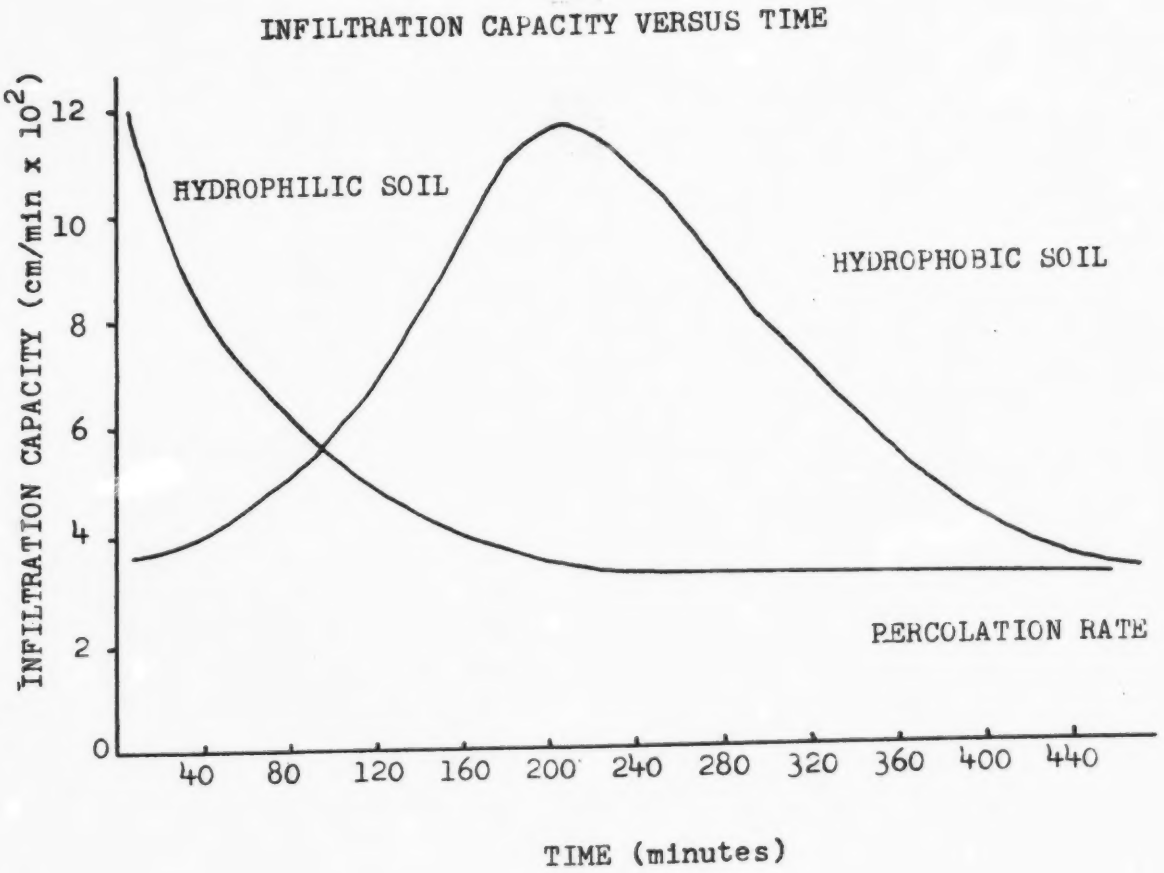

Figure 12. A graph of infiltration capacity vs. time for hydrophilic ("normal") soils and hydrophobic (repellant) soils. Hydrophilic soils have a high initial infiltration capacity which decreases to the percolation rate as soil pores become filled. Hydrophobic soils must initially overcome a repellant state before they absorb moisture. Therefore hydrophobic soils have an initially low infiltration capacity which increases as they become "wetted". The capacity then drops as soil pores become filled.
(Source: after Betey et al., 1962)

Concrete soil frost consists of many very thin ice lenses and small crystals, and has an extremely hard structure. It is the characteristic frost in large, bare, open areas. Concrete soil frost is impermeable, but in forest soils it is usually traversed in placed by large unfrozen areas that allow water to infiltrate (Byrnes, 1951; Trimble et al., 1958).

Reduction in infiltration capacity only becomes a problem when it is reduced below the precipitation intensity. For example, Willington (1969) found that broadcast burning reduced infiltration capacity from 46 to 34 cm per hour on one site, and from 66 to 46 cm per hour on another. Both reduced values are still three to four times the maximum precipitation intensities for the area. In other areas with low initial infiltration capacities which are severely burned, the resulting rates may be below the precipitation intensities. This situation is most likely to occur in areas which experience high intensity convection (thunder) storms. When the infiltration rate is exceeded, overland flow results, causing soil erosion and a reduction in the amount of water taken into the soil.

c. Surface erosion

The erosion potential following broadcast burning is related in part to the inherent erodibility of the soil itself. Thus on some sites the hydrologic modifications due to broadcast burning will not result in an increase in soil erodibility. On other sites it may tip the balance or aggravate an already erodible condition.

Willington (1969) noted that the key parameter in determining erosion is the infiltration rate of the soil, implying that in order to have surface erosion, overland flow is necessary. However two types of surface erosion - dry ravel and raindrop erosion - can occur on soils with high infiltration rates and no overland flow.

Mersereau and Dyrness (1972) studied erosion following clearcut harvesting and broadcast burning in a 96 hectare watershed with average slopes of 65%. They found that erosional losses were greater during the dry season (265 cu ft/ac or 18.5 m^3/ha) than during the wet season (44 cu ft/ac or o.5 m^3/ha). Similar results were obtained by Anderson et al. (1959). The major form of surface erosion observed in both studies was dry ravel. Dry-season debris movement on steep slopes may be an important cause of mortality in plantations, thus making reforestation a slow process (Franklin and Rothacher, 1962; Mersereau and Dyrness, 1972).

Studying soil erosion on broadcast burned areas, Sartz (1953) found an almost complete lack of evidence of surface runoff, but observed and measured soil loss. He concluded that soil displacement was due to splash erosion from raindrops. Observations of soil pedestals (Photo 3) and their subsequent disappearance, and the later appearance of many fine roots support this conclusion. During the first year after the fire, the area became revegetated. Sartz (1953) felt that this cover would significantly reduce erosion. However, on sites which do not revegetate quickly, soil erosion could be significant.

Dyrness et al. (1957) reported that on lightly burned areas, soils were not significantly more erodible than undisturbed soils. In contrast, the erosion potential on severely burned sites should be increased due to a number of reasons: removal of organic matter, exposure of mineral soil, destruction of soil structure, and reduction in clay content due to fusion. However, Dyrness et al. (1957) noted three factors which tend to minimize the danger of surface erosion from these areas: (1) often a protective crust is present on the soil surface of severely burned areas; (2) the severely burned sites tend to be small and in discontinuous patches, and (3) most severely burned sites are on gentle slopes and benches due to slash accumulations, not on the steep slopes where erosion is apt to occur.*

Numerous studies agree with the conclusion of Mersereau and Dyrness (1972) - on any steep, unstable area or areas with long anticipated revegetation periods, other means of slash disposal such as clean yarding or chipping and returnign slash to the slope should be considered as alternatives to broadcast burning.

d. Soil moisture

As noted previously, forest harvesting results in a reduction in evapotranspiration and thus an increase in soil moisture content.

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* It should be noted that these conclusions are perhaps conservative since almost half of the study clearcuts remained untouched by fire.

Photo 3. Soil pedestals are tiny columns of soil beneath a protective cap (e.g. rock fragment) and are a characteristic feature of raindrop erosion.

Broadcast burning can also influence soil water. A number of studies have found a reduction in the moisture content and capacity in the upper layer of the soil (Austin and Baisinger, 1955; Beadle, 1940; Dyrness et al., 1957; Haines, 1926; Heyward, 1939). This has been attributed to a reduction in soil porosity, destruction of soil structure, modification of texture through the fusion of clay particles, reduction in organic matter content, formation of a hydrophobic layer, and the presence of a black soil surface which absorbs more heat, thus enhancing evaporation. The reduction is proportional to the intensity of the burn, with severe burns significantly reducing the soil moisture content and capacity.

The depth of the surface layer affected is variable, with from (1.25 to 5 cm) being reported (Austin and Baisinger. 1955; Dyrness et al., 1957). Where hydrophobicity is present the affected depth can be another (five to 10 cm) (DeBano and Krammes, 1966). While natural regeneration would have difficulty in establishing, planted stock could conceivably receive sufficient moisture by extending through the moisture lacking soil layers. Although not reported in the literature, it is possible that the hydrophobic layer may act as a barrier to the upward movement of water, thus reducing soil water evaporative losses and maintaining soil moisture levels.

2. Alternate methods of site treatment

While the hydrologic effects of broadcast burning have received rather intensive study, the alternate methods of site treatment have received very little attention. This may be due to the limited use of some treatments (chemical, burying), but in other cases such as mechanical scarification, the lack of attention is surprising, in view of the potential for a hydrologic impact on a site.

Terrain imposes constraints on the implementation of several site treatments. For example, while burying slash is feasible in California (Schimke and Dougherty, 1966), excessive cost, extensive site disturbance, and limitations imposed on tractive equipment by topography, limit its use in mountainous areas of British Columbia (Willington and Jamieson, 1971). Similarly, rock outcrops, slopes greater than 20-30%, and heavy slash accumulations limit the use of

mechanical crushers (Feller, 1972; Roe et al., 1971; Van and Gallagher, 1968).

One site treatment which has yet to be perfected is the use of chemicals to enhance decomposition rates of slash (Hendee et al., 1966). However, the questionable effect, high cost, difficulty in commercial application and distribution of the chemicals, and the possible adverse effects on the ecosystem, limit the use of this method (Willington and Jamieson, 1971).

Another little exploited method of slash disposal is the use of wood rotting fungus (Lindenmuth and Gill, 1959). Needless-to-say, the hydrologic effects on a site through the use of "nature's slash disposal" system, have not been studied.

Portable wood chippers have been used to eliminate the logging slash hazard, and through the production of mulch, also protect the site from surface erosion (Casamajor and Wilson, 1957; Dell and Green, 1968; Wilson, 1970). In steep terrain, mounting chippers on crawler tractors can improve mobility (Fahnestock, 1953), but the effect on soil compaction has been cited as a possible disadvantage (Roe et al., 1971).

The use of mechanical scarification is restricted due to topography in mountainous watersheds. Apparently, for this reason it has received very little hydrologic attention. This is surprising however since it would appear that scarification, through exposure of mineral soil and soil compaction, has a high potential for creating a major hydrologic impact on a site.

In order to dispose of debris following scarification, slash piles are usually burned. The result is often intensely hot fires (Davis, 1959). The effect is similar to severe broadcast burns, but more pronounced. For example, Vogl and Ryder (1969) found that soil color and texture were altered to a depth of (30 cm) due to the intense heat. Erosion channels were observed downslope from former slash piles as a result of increased runoff, and the slowest water infiltration rates were obtained on slash sites in which rainwater had caked fine ash and charcoal into a surface crust. Even 15 years after burning, infiltration rates were over 4 times lower on the burned sites than on the adjacent unburned sites. Soil damage resulted in reduced plant growth that was still very evident 15 years following burning.

Vogel and Ryder (1969) report that windrowing of slash results in less dense collections which they felt should reduce fire temperatures and thus minimize soil damage.

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POOR

QUALITY

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